Low-Cost Rare-Earth-Free Electric Drivetrain Enabled by Novel Permanent Magnets, Inverter, Integrated Design and Advanced Thermal Management

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Project ID # elt263

MARQUETTE UNIVERSITY BE THE DIFFERENCE.

Niron Magnetics

VIRGINIA TECH

NREL Transforming ENERGY

GM

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project start date: October 2020
- Project end date: January 2024
- Percent complete ~10%

Budget

- Total project funding:$6,250,000
  - DOE share:$5,000,000
  - Contractor share: $1,250,000
- Funding for FY 2022:$1,443,209

Barriers and Technical Targets

- Barriers addressed
  - Develop a rare-earth free electric drivetrain while maintaining motor performance and avoiding irreversible magnet demagnetization
  - Develop a low-cost electric drivetrain with systems cost $\leq \$7/\text{kilowatt}$
  - Develop an electric drivetrain with systems power density ≥ 12 kW/liter
  - Develop an electric drivetrain with DC bus voltage ≥ 700 V

Partners

- Marquette University (Lead)
- Niron Magnetics
- Virginia Tech
- NREL
- General Motors

Relevance

The objective of this project is to research, develop, and test a heavy rare-earth mineral free iron nitride (FeN) permanent magnet enabled electric drivetrain system for use in vehicle applications capable of the following:

Electric Traction Drive System Technical Targets (2)	
Parameter	**Target**
Cost (1)	≤ $7/kilowatt (kW)
Power Density (2)	≥ 12 kW/liter
Operating Voltage	≥ 700 V

Notes:

(1) Calculate cost based on 2020 equivalent dollars. The cost does not include cases, shielding, or external connectors/connections.

(2) Calculate based on peak power capability for a duration of at least 10 seconds with volume based on overall outer bounding dimensions. Volume does not include cases, shielding, or external connectors/connections.

The objective is to develop next generation low-cost rare-earth-free electric drivetrains

Milestones (BP1:Q1-Q5)

Milestone	Type	Description
Down select and develop preliminary motor designs	Technical	Developing preliminary motor designs that eliminate/reduce rare-earth material and that provide a path to meet system-level targets.
Demonstrate FeN packing factor	Technical	Achieve volumetric packing factor > 95% of theoretical density
SiC MOSFET selection	Technical	Select and test device switching performance and establish loss data and efficiency projection
Preliminary inverter design validated to achieve performance metrics	Go/No Go	SiC inverter system design passes the critical design review (CDR) against design matrix (30 kW/L power density, 98.5% efficiency), Final design Bill-of-materials (BOM) and cost analysis report is generated to meet the cost target. Sub-components are designed and tested.

Currently BP1 ends by 12/31/2022

Milestones (BP2:Q6-Q9)

Milestone	Type	Description
Motorettes test results	Technical	Motorettes tested and results match predictions. Proposed thermal management (and material selection) can maintain a hot spot below 180^{o}C and no signs of irreversible demagnetization.
Heavy rare-earth-free motor test results	Technical	Sub-scale/Full-scale heavy rare-earth-free motor built and tested (Peak torque up to 360 Nm and motor power density >16 kW/L achieved with no signs of irreversible demagnetization)
Inverter assembly, test, and validation	Technical	Finish assembly and testing of 200 kW inverter unit at full power and confirm performance specifications.
Produce test coupon	Go/No Go	Produce 100 gram coupon with 36 MGOe energy product

The timeline will change due to various logistical delays

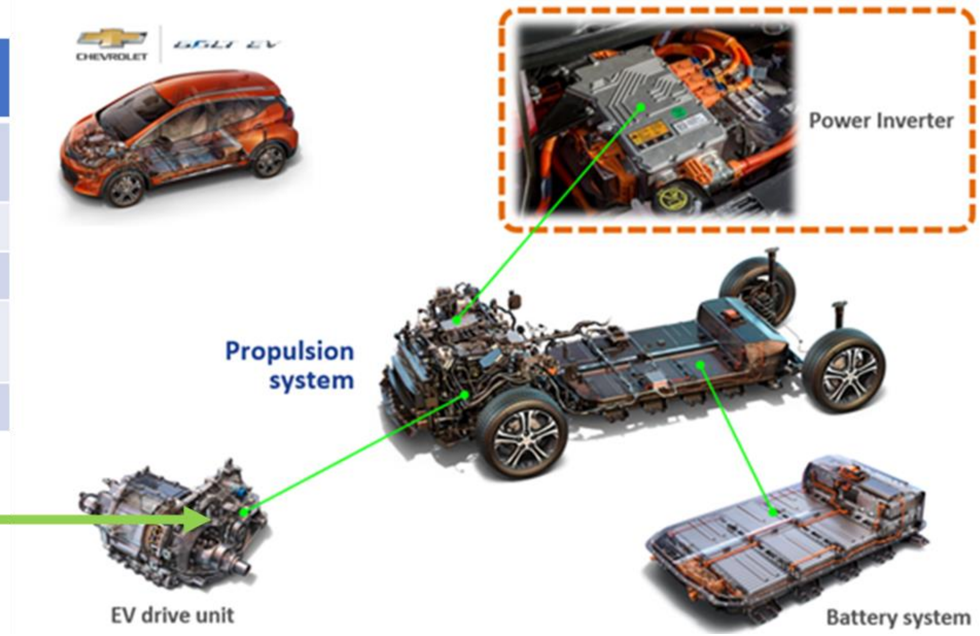
Milestones (BP3:Q10-Q13)

Milestone	Type	Description
Produce 2 kg fully dense magnets	Technical	Scale nanoparticle coating recipe to 2 kg capacity and produce 2 kg of magnets with 36 MGOE
Motor protype built	Technical	Rare-earth-free motor prototype built and ready for system integration
Inverter thermal-mechanical integration	Technical	One inverter unit is fully packaged and tested for full-power condition of 200 kW
System verification testing	Technical	Full system tested to verify performance targets of $\leq$ \$7/kW, $\geq$ 12 kW/l, and $\geq$ 700 V. System verification testing (torque-speed curve and efficiency map generated)

The timeline will change due to various logistical delays

Approach: Baseline System

	Chevy Bolt (Baseline)	Proposed
Max Torque [Nm]	360	360 or lower depending on speed
Max Power [kW]	150	200
Max Speed [rpm]	8810	up to 16,000 rpm
Max Motor Current [Arms]	400	<350
DC Bus Voltage [V]	<450	700-800



The Chevy Bolt system will be used as a baseline

Approach: Project Scope

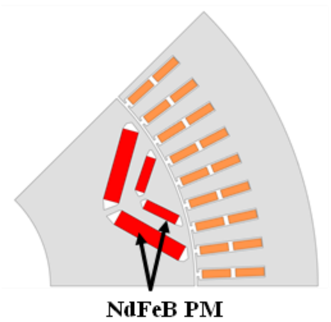
- Budget Period (BP) 1: [Concepts development and tradeoff studies]:
  - Develop concepts, performing tradeoff studies of the various concepts and down-selecting concepts.

- Budget Period 2: [Detailed design, sub-component/component testing and risk retirement]:
  - Develop a detailed design, conduct design optimization, and conduct sub-component/component testing.

- Budget Period 3: [System integration and verification testing]:
  - Procure components, conduct system integration, and perform verification testing.

The proposed approach will enable systematic concepts development and risk retirement

Traction Motor Development Approach



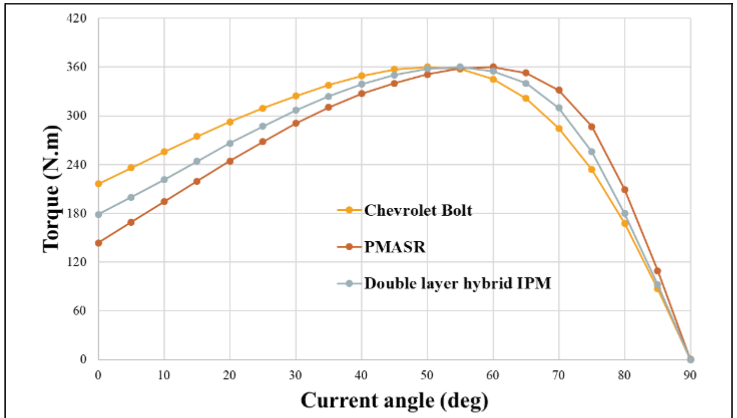
Chevy Bolt IPM motor

Rare-earth free Motor concept 1 Patent pending

Double-layer IPM with blended FeN and Ferrite magnets

Rare-earth free Motor concept 2 Patent pending

PM-assisted synchronous reluctance (PMASR) design with blended FeN and Ferrite magnets

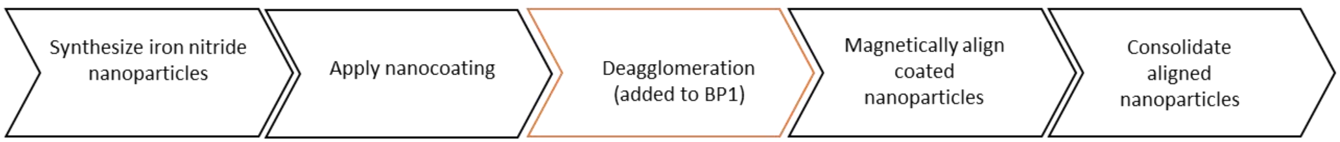


Comparison of torque curves of the three designs

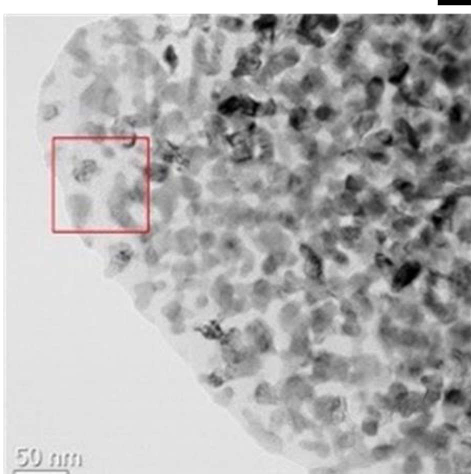
- *A family of designs ranging from elimination of heavy rare-earth material to complete elimination of rare-earth materials will be developed and design tradeoffs documented*
- *Preliminary designs indicate that torque producing capability of a baseline rare-earth IPM can be met with the proposed concepts*
- *The final design is expected to either combine ferrites with FeN magnets or only use FeN magnets*

FeN Magnets Development Approach

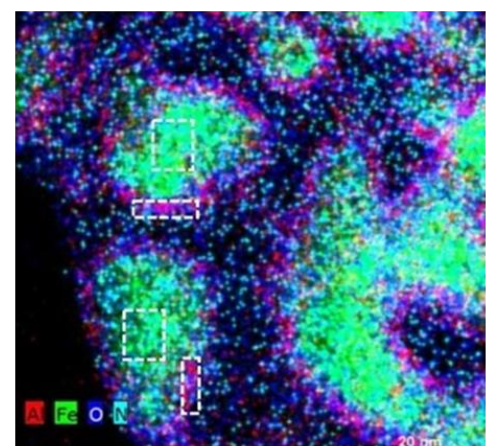
- Niron is manufacturing iron nitride permanent magnets from coated nanocrystalline powders
- Niron is developing low-temperature alignment and consolidation routes to produce high energy product (36 MGOe) iron nitride permanent magnets
- Selection of deagglomeration process by chemically-assisted milling pulled in to BP1. It was determined that this process had to be included to ensure that consolidated powders could be aligned



Iron nitride magnet manufacturing process



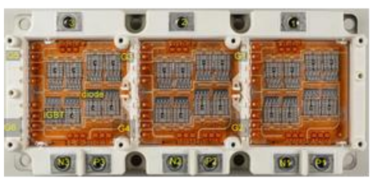
Iron-based nanoparticle precursors



Coated iron nitride nanpoarticles

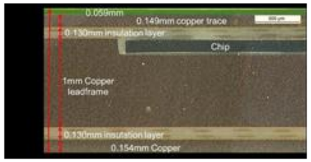
Inverter Development Approach

- **1.2 kV discrete SiC MOSFETs**: lower $/kW device cost due to high voltage high efficiency operation
- **Single Heavy Copper PCB bus structure** to integrate device, gate-driver, sensor: lower manufacturing and assembly cost.
- **High-temperature Automotive qualified ceramic capacitors**: significantly improve power density due to 5X higher power density than film cap.
- **PCB-embedding Device integration**: lower transient voltage stress enabling use of lower voltage class devices for lower $/kW
- **PCB-based coil and SMD Hall IC** for current sensing and protection: lower sensor costs



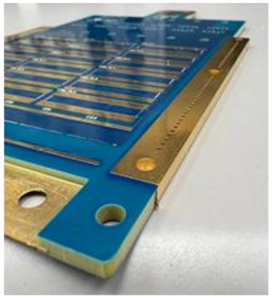
IGBT module

SiC MOSFET



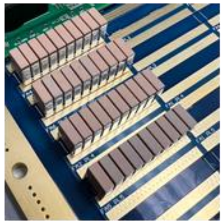
PCB embedding

Conventional bus-structure



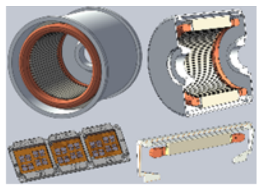
Heavy copper PCB bus

Customized film-cap

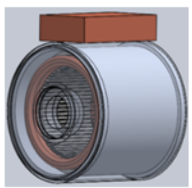
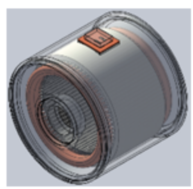
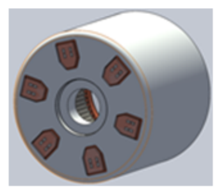


HT Ceramic cap

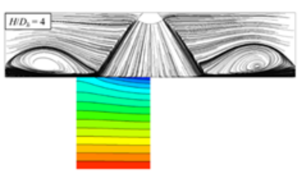
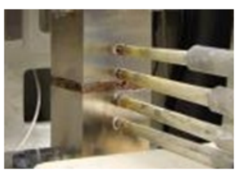
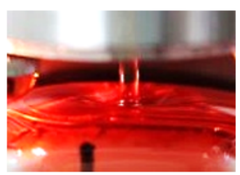
Thermal Management Development Approach



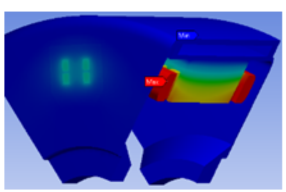
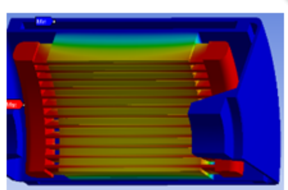
Develop Component Designs and Technologies for Motor and Power Electronics

Evaluate Integration approaches

Research and characterize thermal management improvements for active and passive heat transfer technologies

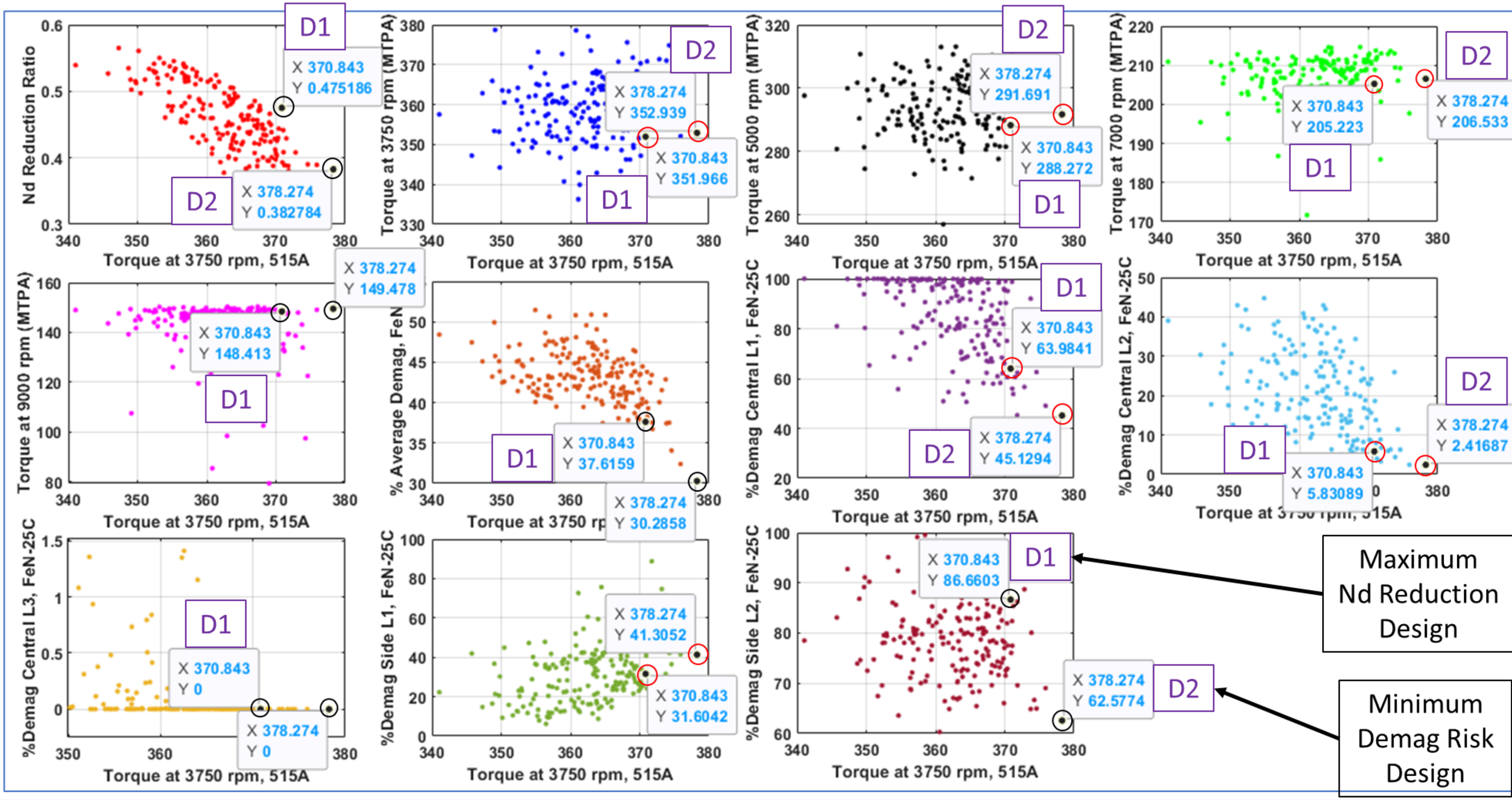
Evaluate cooling solutions with numerical modeling

- Establish performance targets
- Support design tradeoff studies

Image sources: Emily Cousineau, Xuhui Feng, Bidzina Kekelia of NREL

Technical Accomplishments

Optimized Designs that Reduce/Eliminate Rare-Earth Material



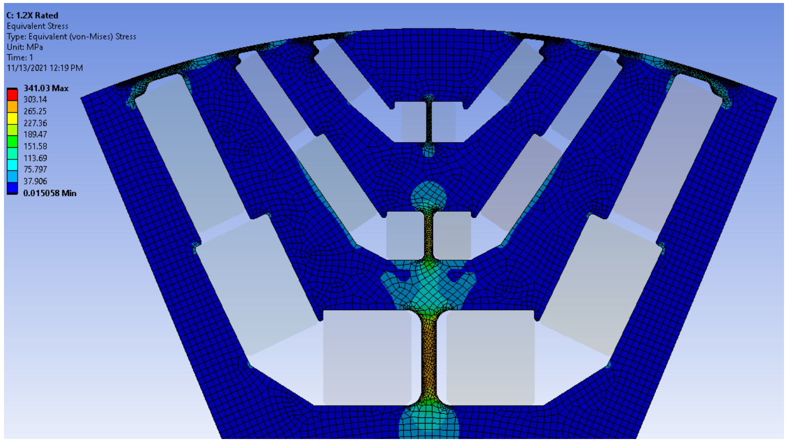
- *A differential evolution (DE) coupled with FEA optimization tool has been developed*
- *The tool has been applied to optimize various motor topologies under consideration*
- *For each topology the focus is on designs that achieve maximum rare-earth reduction as well as minimum demagnetization risk*

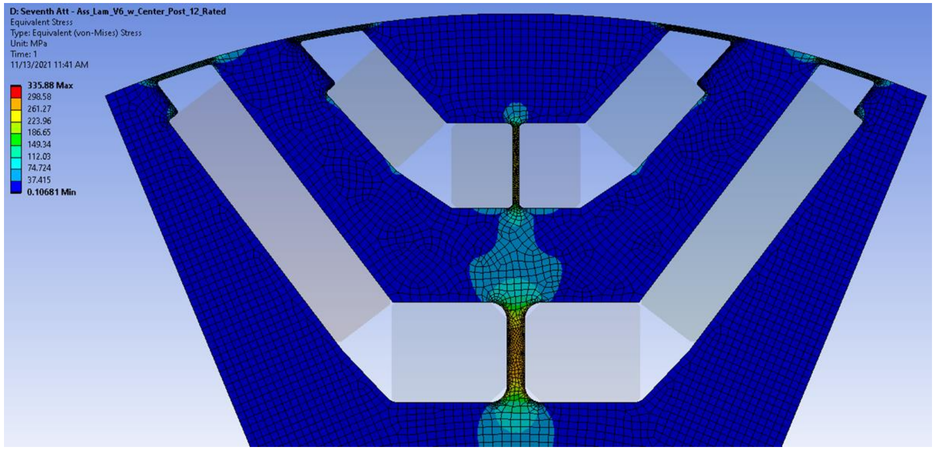
Technical Accomplishments Preliminary Optimization Results

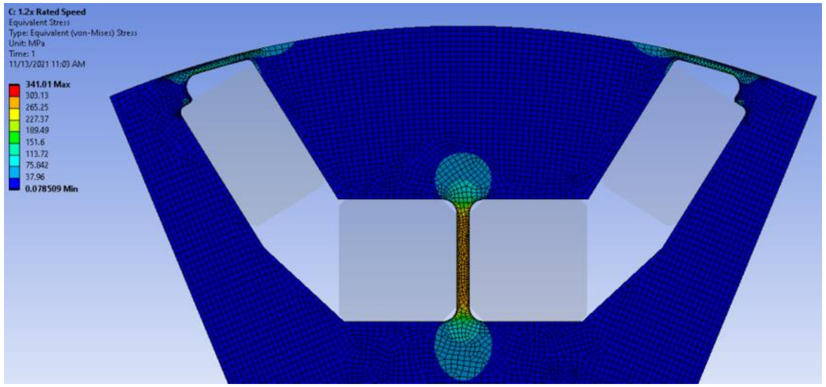
	Chevy Bolt	Nd+Ferrite_Max Nd Reduction	Nd+Ferrite_Min Demag Risk	Dy-free+Ferrite_Max Nd Reduction	Dy-free+Ferrite_Min Demag Risk	FeN+Nd_Max Nd Reduction	FeN+Nd_Min Demag Risk	FeN_Min Demag Risk
Torque base speed (Nm)	364.4	358.5	369.1	359.65	359.65	370.84	378.27	336.7
Nd Reduction ratio	0	50.0%	38.9%	36 %	36 %	47.5 %	38.3 %	100%
Demag risk Back-emf analysis (-20C)	0	2.6%	0.81%	0.31 %	0.31%	16.32 % (At 25 C)	11.9 % (At 25 C)	2.3%
Demag risk Back-emf analysis (150C)	0	0.58%	0.55%	0.48 %	0.48 %	16.17 %	11.74 %	2%
T_5000rpm(Nm)	292.9	304.4	321.8	269.92	269.92	288.27	291.7	287
T_7000rpm(Nm)	199.83	199.8	214.6	185.9	185.9	205.22	206.53	192.7
T_9000rpm(Nm)	148.12	124.2	139.5	133.7	133.7	148.41	149.48	130

- *Various designs are different degrees of maturity*
- *Multiple designs completely eliminate heavy rare-earth material with significant reduction of light rare-erth material (~40%-50% depending on the design)*
- *Some designs have higher demagnetization risk and still require further work*
- *Designs with only FeN magnets show promising results including very low risk of demagnetization and ~8% lower torque compared to the baseline design (performance should improve with further optimization)*

Technical Accomplishments
Motor Mechanical Analysis





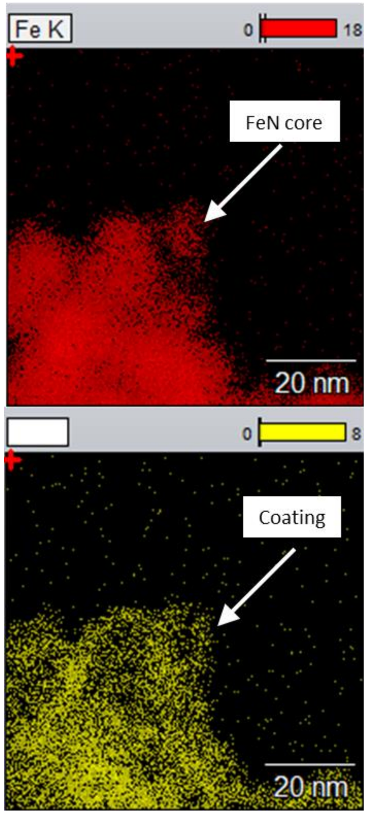


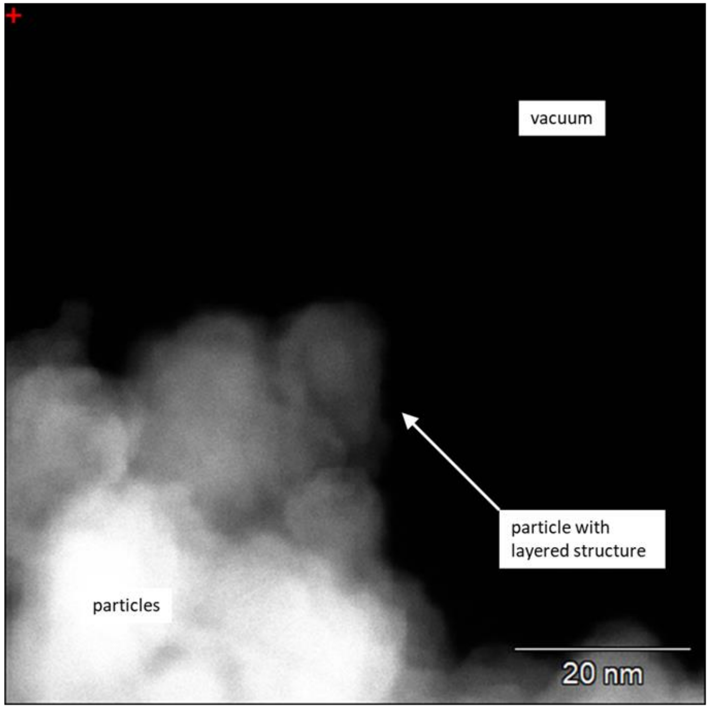
- *Mechanical FE analysis performed on 1,2, and 3 layers of magnets at 20% overspeed*
- *This provided preliminary mechanical sizing of bridges and center/side posts that was fed into the motor optimization process*

Technical Accomplishments
Iron Nitride Magnets

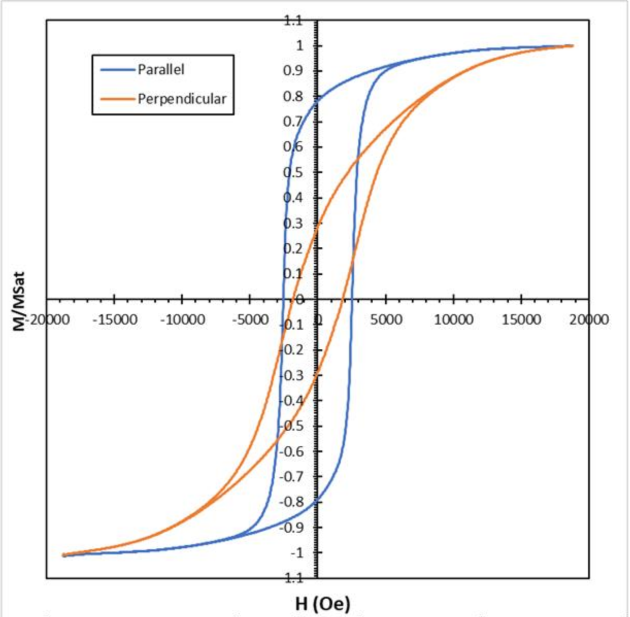
- 70 grams of coated nanoparticles produced
- Uniformity and composition of coating verified
- Uniaxial compaction curves measured
- Deagglomeration of nanoparticles by chemically assisted milling demonstrated
- Tooling for shear assisted compaction designed and being fabricated

Technical Accomplishments
Iron Nitride Magnets





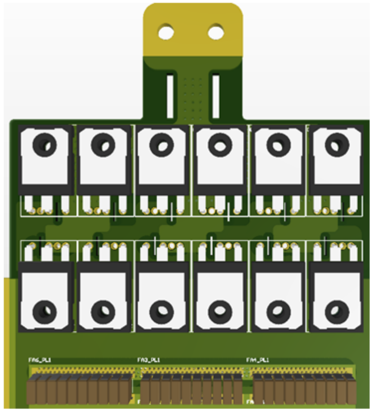
Transmission electron microscopy of coated iron nitride nanoparticles. Chemical maps verify presence of uniform coating.



Hysteresis loops measured on deagglomerated nanoparticles dispersed and magnetically alignment in epoxy. Loops were measured with the applied field oriented parallel to and perpendicular to the alignment direction. The alignment is indicated by the difference in squareness between the two measurement directions.

Technical Accomplishments
Traction Inverter

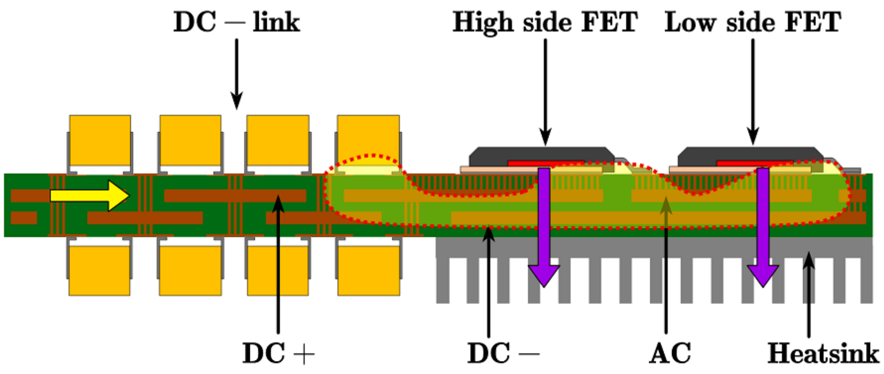
Design1: Discrete Device Design



Key challenges:

- PCB layout comparison for low loop inductance & low overlapping capacitance
- Integrate AC busbar, DC busbar, current sensor into 1 heavy copper PCB
- Current density performance

Design2: Embedded PCB Design



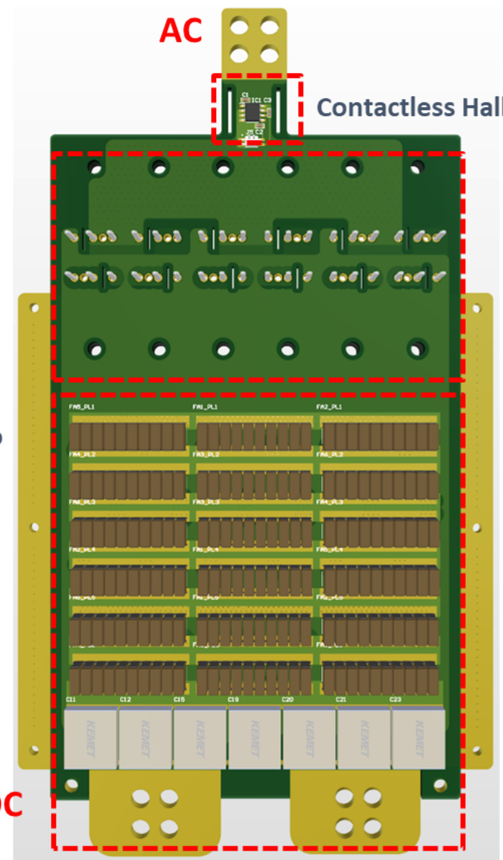
Key challenges:

- Current commutation loop inductance
- Thermal conductivity
- Current density

Technical Accomplishments
Traction Inverter

Design1: Power Board Design (Single-phase)

AC



Connect to enclosure

DC

Contactless Hall Sensor: MLX91208

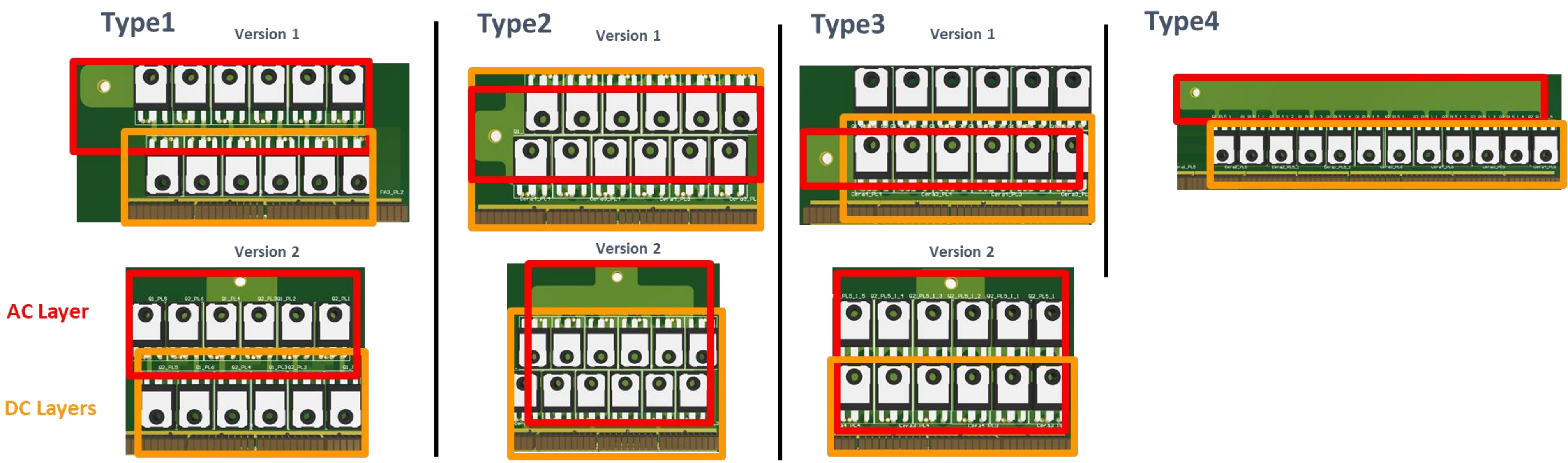
SiC MOSFET: MSC017SMA120B4

DC-Link Capacitors: CeraLink

<u>Key findings:</u>
Integrate AC busbar, DC busbar, current sensor into 1 heavy copper PCB
Current commutation loop stray inductance around $3\ nH$
Replace bulky film capacitor with low profile ceramic capacitor

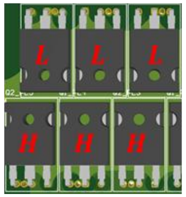
Technical Accomplishments
Traction Inverter

PCB Layout Comparison for Discrete Devices

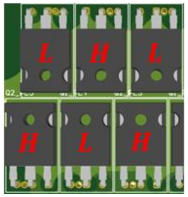


Device Arrangement

Sequential:



Interleaved:

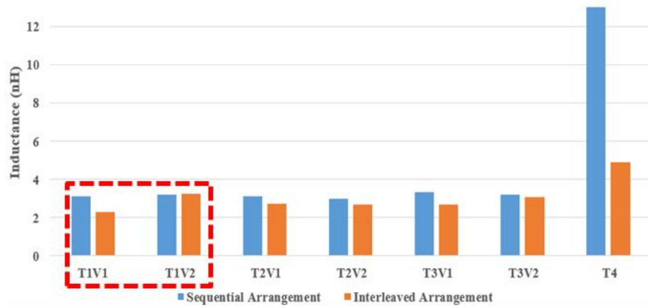


- ✓ In total 7 different layout structures are compared
- ✓ Also, 2 different arrangements of device are considered

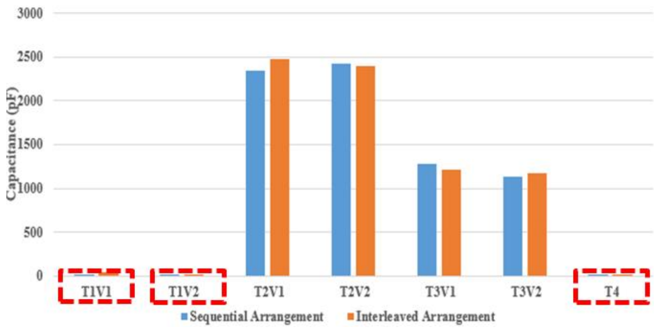
Technical Accomplishments
Traction Inverter

PCB Layout Comparison for Discrete Devices

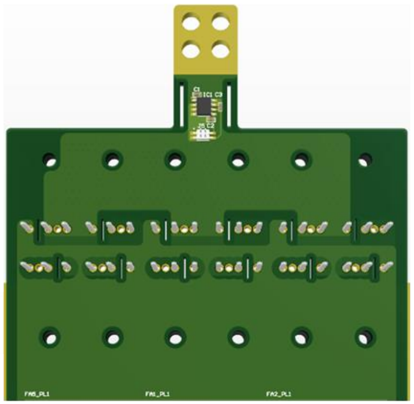
Stray Inductance Comparison:

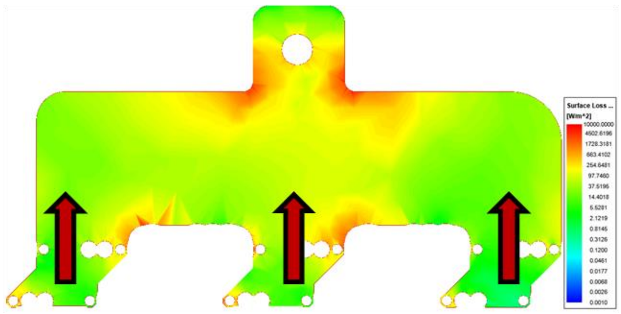


Overlapping Capacitance:



Current Density Performance: at $f_{ac} = 20\ kHz$

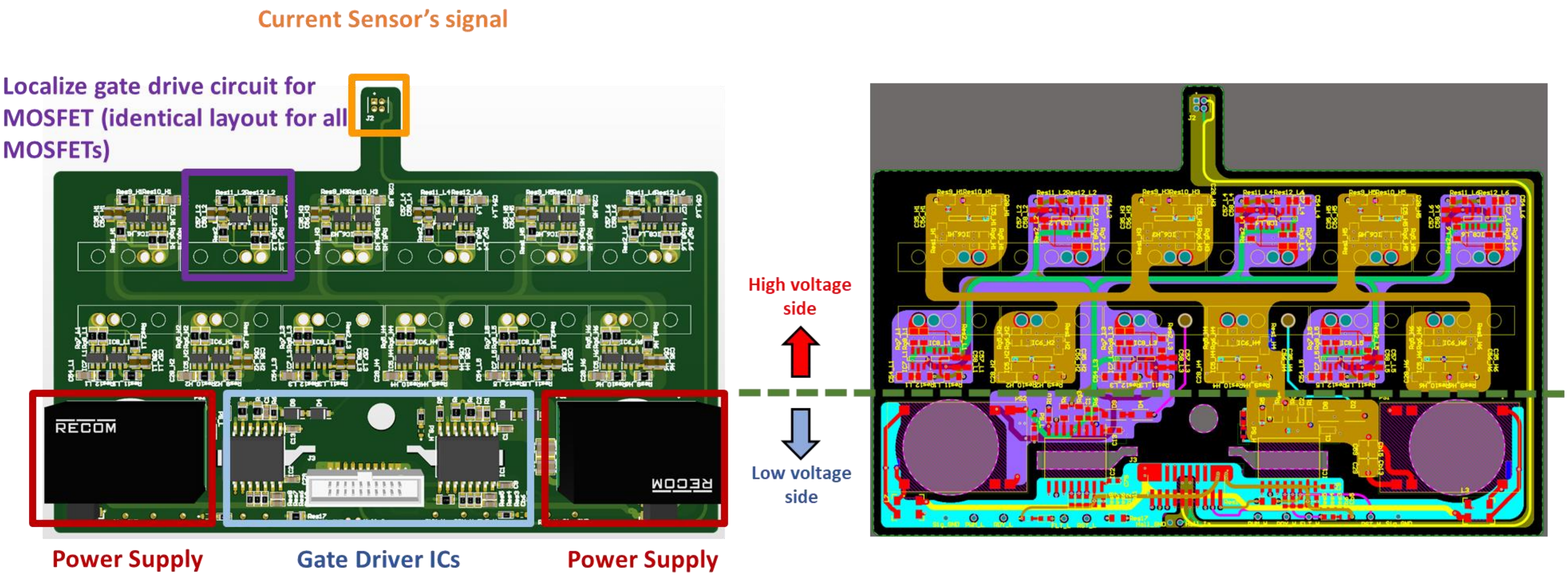




$I_{excite,1} = 100\ A$ $I_{excite,2} = 100\ A$ $I_{excite,3} = 100\ A$

✓ Type1 Version2 has low stray inductance (lower voltage stress) and low overlapping capacitance (lower induced switching loss), and more balanced current sharing performance, therefore, is selected as final layout

Technical Accomplishments
Traction Inverter

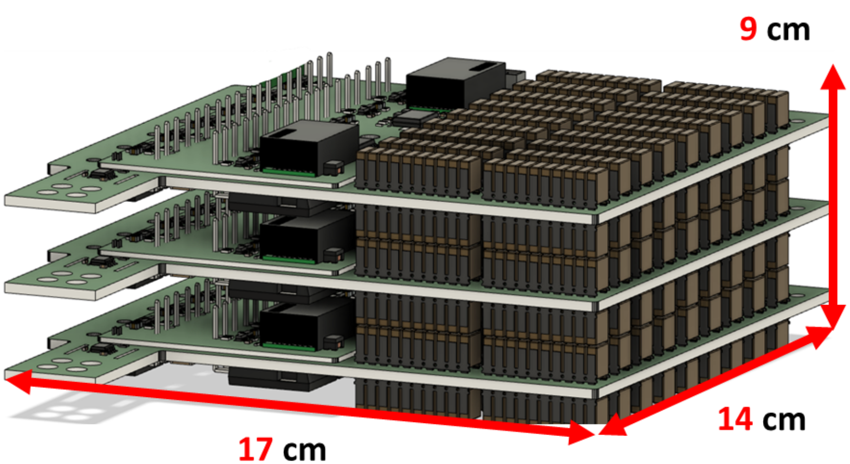


- ✓ **Connect power board and gate driver board by using pins of TO-247-4L package, reduce connectors between power board and gate driver board**

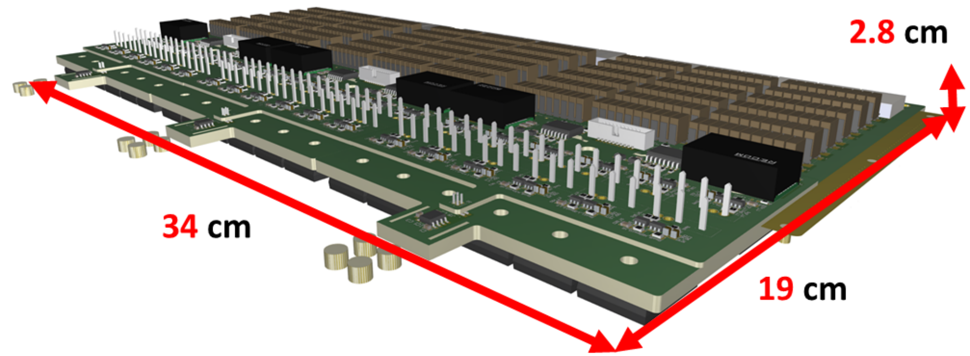
Technical Accomplishments
Traction Inverter

3-Phase Inverter Assembly Options

Option 1: cube-like design



Option 2: Low profile design



- ✓ **Power density: $93.4\ {}^{kW}/_{L}$**
- ✓ **Require separate cold plate**

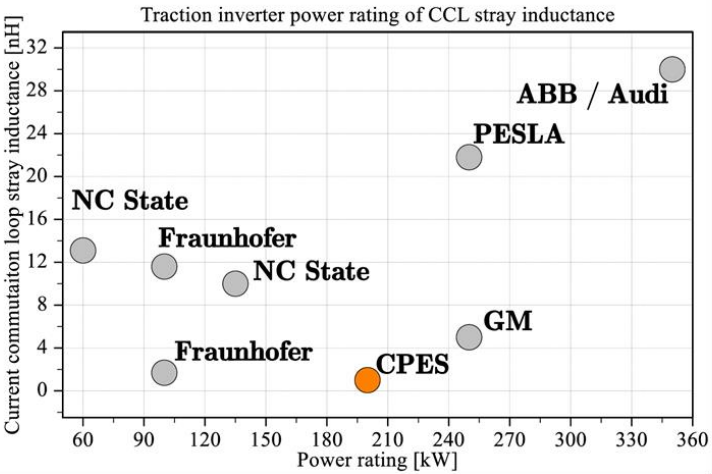
- ✓ **Power density: $110.18\ {}^{kW}/_{L}$**
- ✓ **Require only 1 cold plate**

- ✓ **Final assembly design can be adjusted based on motor's physical structure**

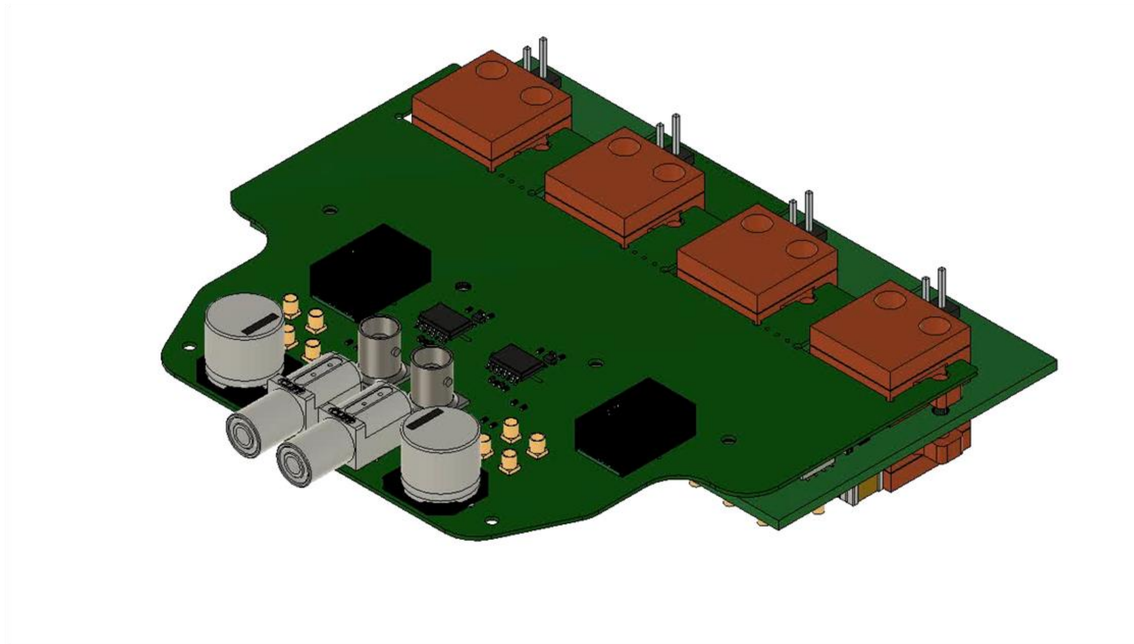
Technical Accomplishments
Traction Inverter

Design2: Embedded die 900V SiC. MOSFET PCB Design for Automotive Traction Inverters

Traction inverter comparison:



Embedded die half bridge design:

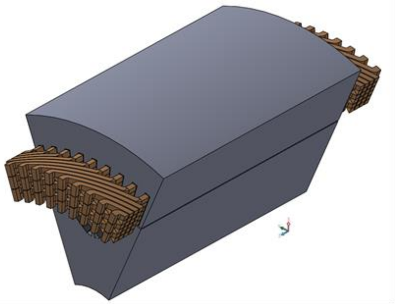


Key findings:

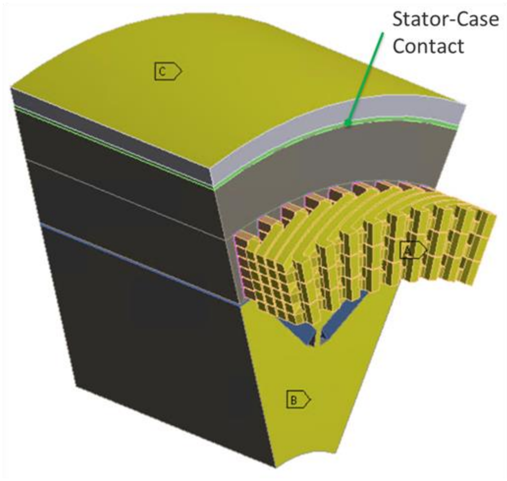
- MOSFET loss reduction of 39%
- Current commutation loop stray inductance is 1 nH
- Thermal resistance reduction of 40%

Technical Accomplishments Motor Thermal Management

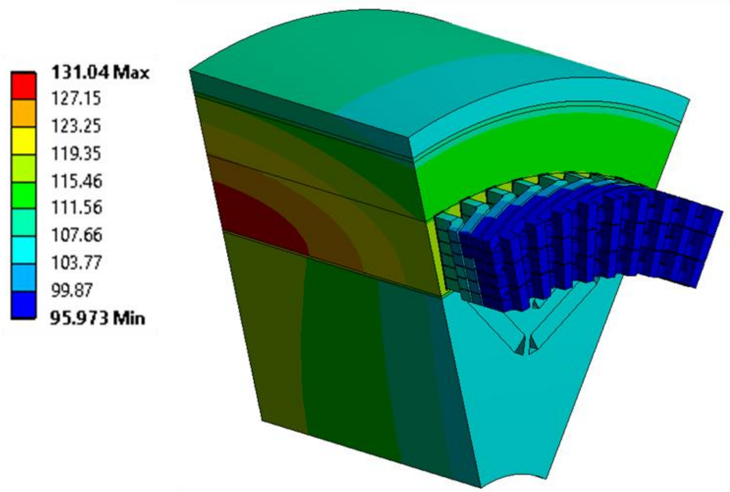
- NREL refined previously developed models for baseline motor thermal comparisons
- Refined cooling boundary conditions and material properties
- Performed parameter sensitivity study on boundary conditions to improve confidence in thermal model



Motor section with ending windings full end winding geometry



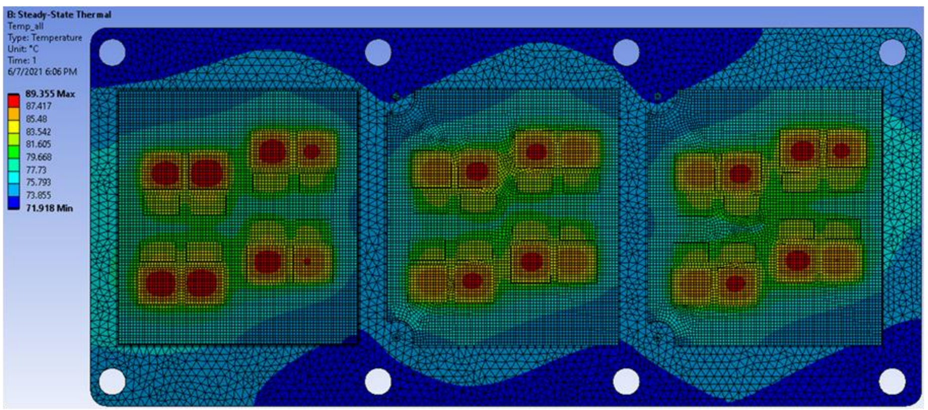
Updated thermal model boundary conditions and thermal contact resistance between stator and case



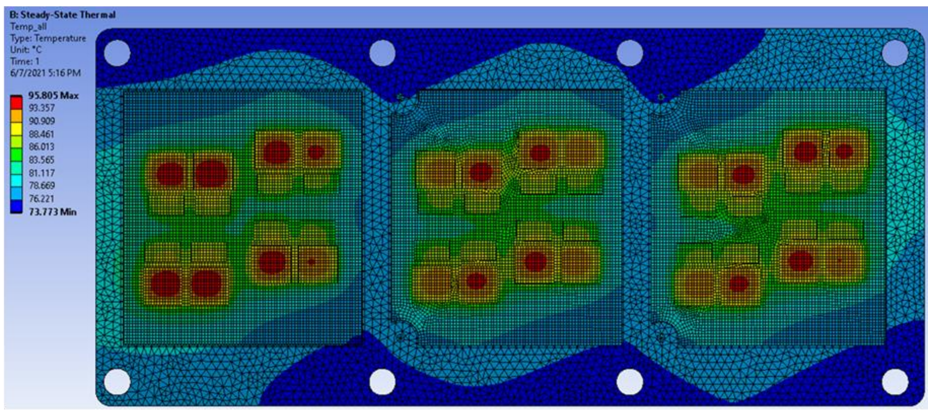
Baseline results well within 150°C temperature limits using estimated loss estimates from project collaborators

Technical Accomplishments
Inverter Thermal Management

- Incorporated loss estimates (heat loads) from Virginia Tech at two operating switching frequencies (10kHz and 15 kHz)



Switching frequency of 10kHz with 65°C inlet coolant and maximum device temperature of 89°C



Switching frequency of 15kHz with 65°C inlet coolant and maximum device temperature of 96°C

Technical Accomplishments
System Integration

- Prepared preliminary Pugh Matrix for comparison of alternative system integration approaches
- Future efforts will work to establish quantitative metrics for comparisons

Options
Inverter and Motor Separate (Baseline)
Inverter axial mount around motor
Inverter axial mount one side
Inverter radial mount around motor
Inverter radial mount on one side of motor
Located in center of motor stator
Located in center of rotor hub

Ranking Categories	Mass, diameter, length, access for repair, cable length…

Ranking Category	Total PE and Motor Weight or Mass	Size: Total PE and Motor Diameter	Size: Total PE and Motor Length
Ranking Weight (1: low, 10 High)	10	10	10
Score meaning	1: Heavy no sharing of parts 5: Significat passive mass reduction	1: Larger diameter 5: Smaller diameter	1: Longer 5: Shorter
Options			
Inverter and Motor Separate (Baseline)	1	2	4
Inverter axial mount around motor (with or without shaft)	5	5	2
Inverter axial mount one side	5	5	2
Inverter radial mount around motor	7	2	5
Inverter radial mount on one side of motor	6	2	5
Located in center of motor stator	8	5	5
Located in center of rotor hub	4	5	4

⋮

…

PE cooling shared with motor end-winding cooling	Applies to inner-rotor motor	Applies to outer-rotor motor	modularity to repair
10	10	10	10
1: Not shared 5: Inverter and motor shared cooling	1: no 5: yes	1: no 5: yes	1: no, must remove full drive system 5: yes, can replace inverter without removing drive system
ative attributes.)			
2	5	5	5
4	5	5	1
4	5	5	4
3	5	1	1
3	5	1	4
1	1	5	1
4	5	1	2

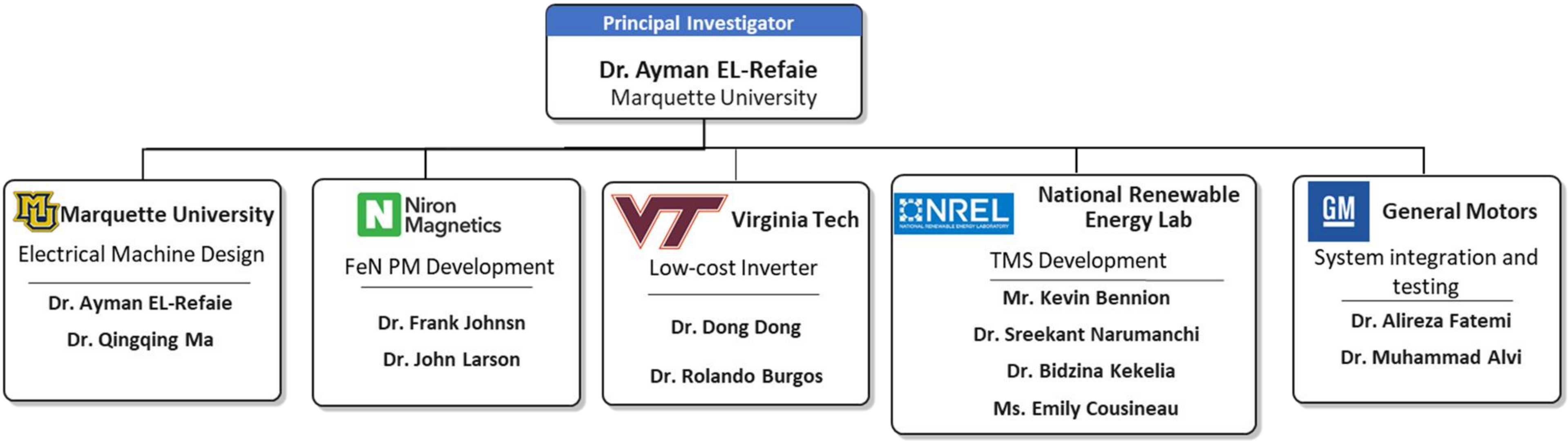
Total Scores

Weighted Category Ratings

Responses to Previous Year Reviewers' Comments

- New project and there were no comments

Collaboration and Coordination with Other Institutions



- *A diverse and experienced team will develop various aspects of the electric drivetrain system*
- *Regular team meetings are taking place to discuss progress made and next steps*

Remaining Challenges and Barriers

- The project is still at a relatively early stage, but the key challenges include:
  - Being able to develop FeN permanent magnets with the target properties
  - Being able to develop a traction motor that completely eliminates rare-earth material without significantly compromising performance
  - Being able to meet the cost and power density targets for the inverter
  - Being able to develop an effective and fully integrated thermal management system

Proposed Future Research

- Consolidation of coated iron nitride nanoparticles to reach iron nitride volume fraction of 95% (BP1 Milestone)
- Development of magnetic alignment methods needed to enable energy product of 36 MGOe (BP2 Milestone)
- Develop and evaluate a wide range of traction motor designs starting from reducing the rare-earth content all the way to complete elimination and quantifying the performance tradeoffs
- Some of the inverter hardware components are expected shortly and verification testing will start
- Continue to evaluate thermal management schemes and develop motor/inverter integration concepts with shared thermal management

Summary Slide

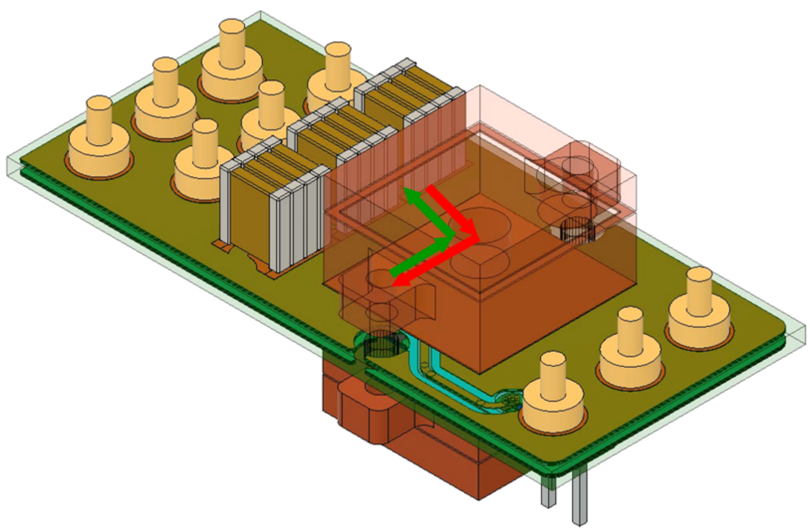
- The project provides a comprehensive approach to meet the demanding DOE systems requirements in terms of cost, power density, higher DC bus voltage and eliminating rare-earth materials
- Several novel technologies and approaches are proposed and are expected to significantly advance the state of the art
- The project is still at relatively early stage and even though there have been significant logistical delays, the progress made so far across the entire system components is encouraging and more progress is expected through end of BP1
- Several motor topologies are being optimized and evaluated
- 70 grams of coated iron nitride nanoparticles were produced by Niron. The presence of a uniform coating around each nanoparticle was verified by transmission electron microscopy. The development of a chemically assisted milling process to deagglomerate the nanoparticles was pulled in from budget period 2. This was done to ensure that shear assisted consolidation techniques are able to be applied to nanoparticles that can be magnetically aligned. The tooling needed for shear assisted consolidation was designed and is being fabricated.
- Hardware components of the inverter will be tested within the next few weeks
- Work on system integration concepts initiated

Technical Backup Slides

Technical Accomplishments Traction Inverter

Design2: Current Commutation Loop Stray Inductance Analysis

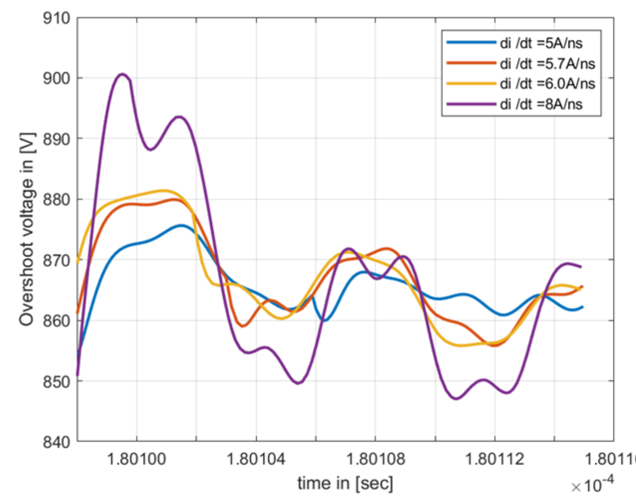
Current commutation loop design:



Key findings:

- PCB stray inductance is $667\ pH$

Overshoot voltage during turn-off transient:



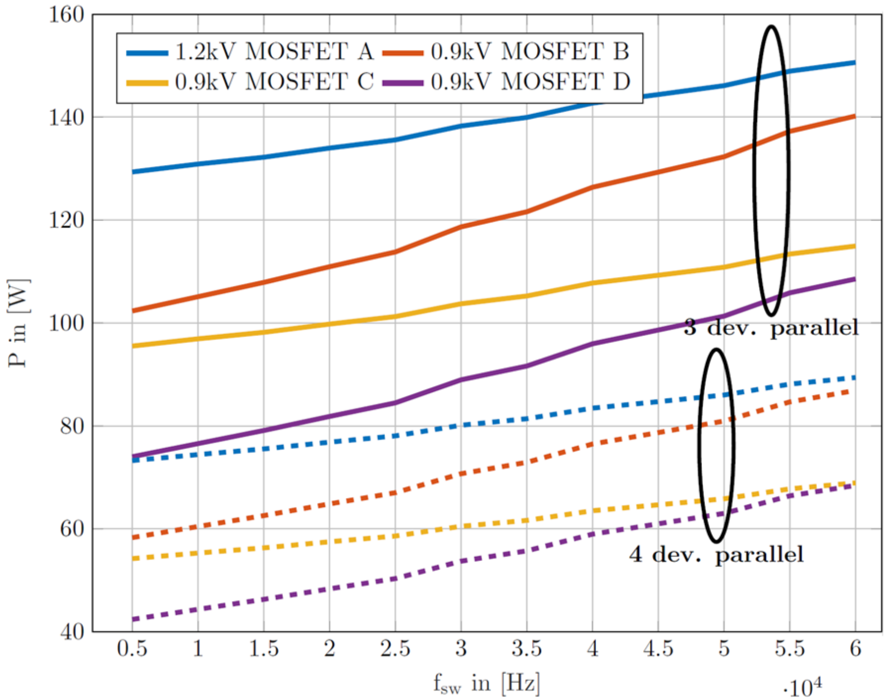
Overshoot voltage at:	
$\frac{di}{dt} = 5\ \frac{A}{ns}$: $V_{DS} = 876V$	$\frac{di}{dt} = 5.7\ \frac{A}{ns}$: $V_{DS} = 880\ V$
$\frac{di}{dt} = 6\ \frac{A}{ns}$: $V_{DS} = 881V$	$\frac{di}{dt} = 8\ \frac{A}{ns}$: $V_{DS} = 901\ V$

Technical Accomplishments
Traction Inverter

Design2: MOSFET loss comparison: 900 V vs. 1.2 kV

MOSFET	Breakdown voltage	$R_{DS,on}$	E_{SW}	Simulated losses @ 3 dev.	Loss reduction %
A	$1.2kV$	$26\ m\Omega$	$720\ \mu J$	$135\ W$	0 %
D	$900V$	$14.5\ m\Omega$	$1453\ \mu J$	$82\ W$	39 %

Embedded die half bridge design:



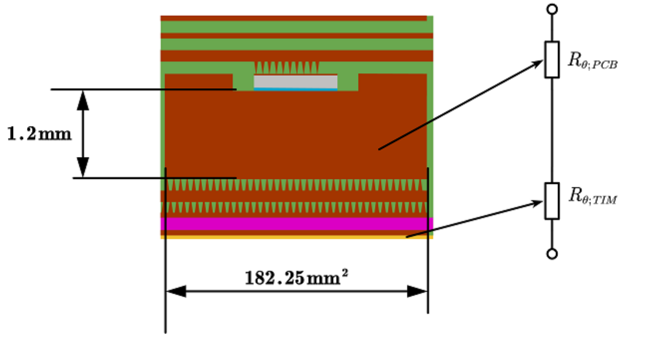
Key findings:

- MOSFET losses can be reduced by 39 %

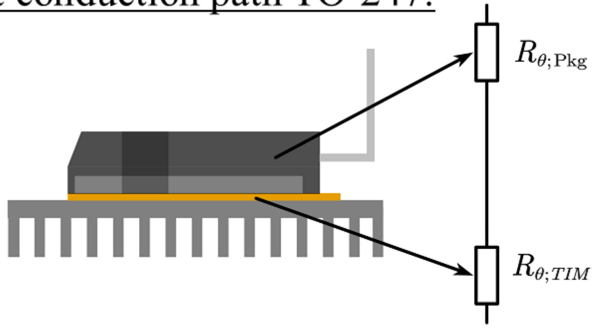
Technical Accomplishments Traction Inverter

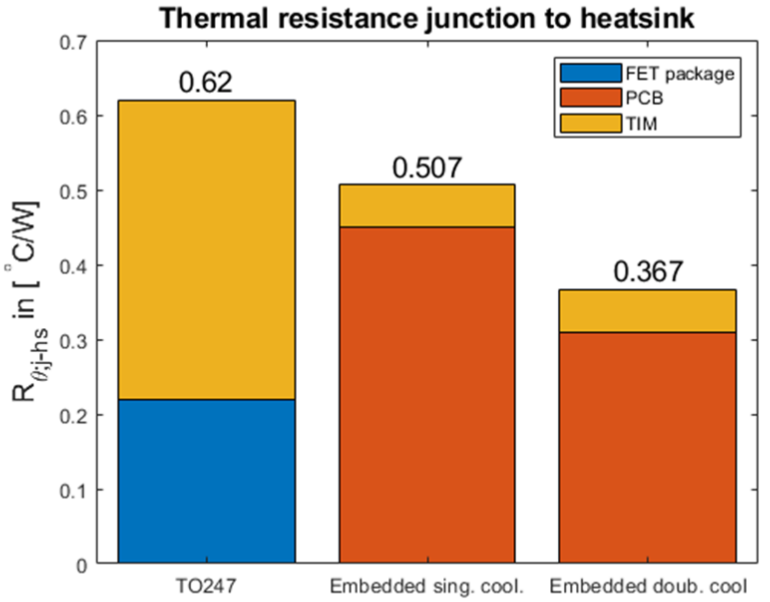
Design2: Thermal Resistance Analysis and Comparison

Heat conduction path embedded:



Heat conduction path TO-247:





Key findings:

- The thermal resistance of a double sided cooled embedded die PCB is 40% smaller than of a TO247 package